X2000 Flight Missions Utilizing Common Modular Components

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Abstract - The X2000 First Delivery engineering model advanced technology spacecraft bus is being developed at NASA's Jet Propulsion Laboratory to enable a challenging and diverse set of interplanetary missions in the first few years of the 21st century. These missions were examined in detail, and a consolidated set of requirements was synthesized to guide the design of the first X2000 bus.

A software and hardware architecture was developed for the X2000 bus that is modular, scaleable, and upgradable. It will enable the procurement of highly capable, low mass flight systems that can perform the mission set at a low recurring cost for the X2000 bus or components of the bus that are used for each mission.

An end-to-end integrated Mission Data System is also being developed as part of the X2000 First Delivery to enable more flexible mission operations. This, combined with a high degree of on-board autonomy will lower the staffing and cost of operations.

1. INTRODUCTION

NASA's Advanced Deep Space System Development Program (ADSSDP) at the Jet Propulsion Laboratory is developing advanced technology components and systems to enable low cost, yet ambitious, missions to the outer planets, Mars, and other destinations in the early 21st century. One of the program's products will be a series of engineering development multimission spacecraft systems which we refer to as the X2000 Buses. The X2000 engineering model spacecraft system deliveries are not planned to be flown, but are to be Proof Test Models (PTM's) to qualify the design and to enable flight units to be procured at a low recurring cost.

The First Delivery of the X2000 Bus is currently under development, with a planned completion date of October 2000. Some of the software development, however, is expected to continue beyond that time. The First Delivery Bus is being designed to be capable of performing both the proposed Europa Orbiter mission and the Pluto/Kuiper Express mission with a common build-to-print spacecraft avionics bus. Mission unique elements, such as science, propulsion modules, and radiation shielding are being designed modularly with standard, common interfaces to minimize cost.

The avionics and engineering sensors in the First Delivery are also being designed to fulfill the needs of other missions, including New Millennium Deep Space 4 (DS-4), Solar Probe, and select spacecraft in the Mars Program mission set. X2000 components and systems would also be available for Discovery missions and Earth orbiting scientific and commercial spacecraft as high performance components with very low mass and low recurring cost.

Flight missions background

The flight missions that will use the X2000 First Delivery bus cover a wide range of targets, science goals, and environmental conditions. Solar Probe operates within 4 solar radii of the sun (3,000 times the solar incidence at Earth, while the Pluto/Kuiper Express mission will operate out to beyond 40 AU (0.0006 times the solar incidence at Earth). The Europa Orbiter will be exposed to 4 Mrad of radiation (behind 2.5 mm of Al), while other missions are well under 100 Krad. The Europa mission requires high data rate telecommunications to recover the science data within its brief lifetime on orbit. Some of the other missions need only minimal data rates.

The DS-4 cometary lander is extremely power constrained, as are the Europa and Pluto spacecraft. All of these missions are mass constrained, but especially so is the Mars Sample Return Ascent Vehicle. Developing a common package of avionics and engineering sensors to meet the requirements of such a mission set is extremely challenging, so modularity, scalability, and upgradability are key to the X2000 architecture.

One possible option for how these missions might be scheduled is presented in Figure 1.

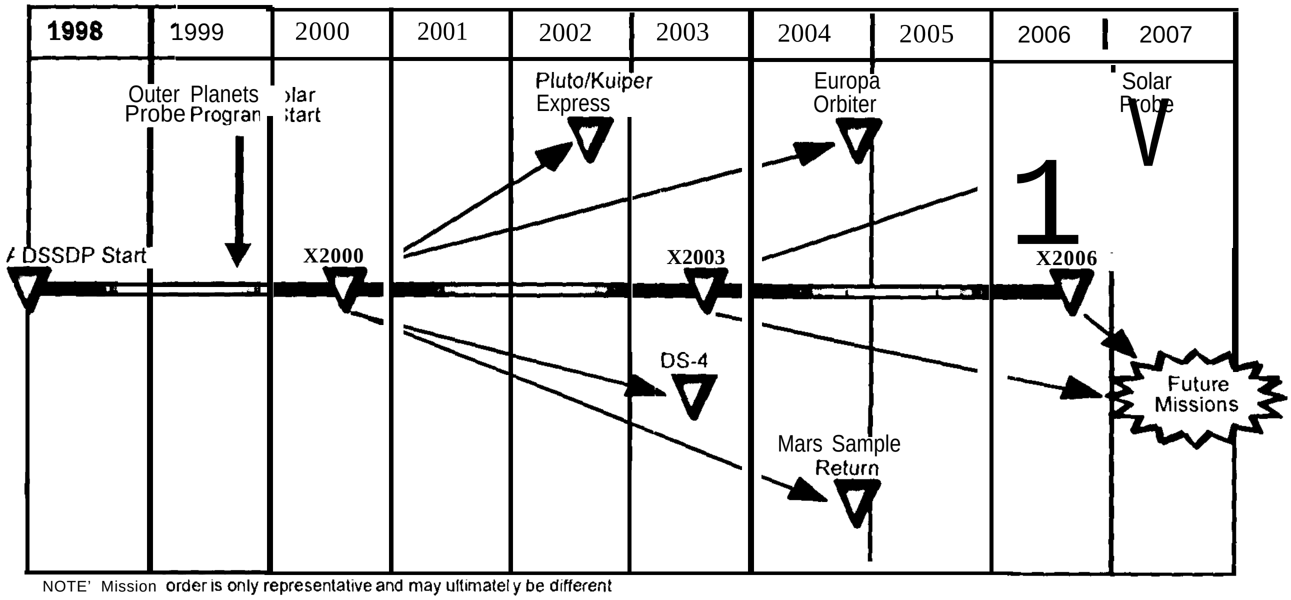

Figure 1: **Sample** Mission Profile Shows Technology **Flow** from **ADSSDP Incremental** Deliveries in Support of Mission Launches

2. MISSION SET SUMMARY

Europa

Jupiter's moon Europa fascinated scientists after the images from the Voyager Mission indicated that the surface of Europa was unusually smooth and lacked visible craters, suggesting that it was very young. Combined with information about its bulk composition, which indicated it had a veneer of water ice, and the knowledge that Europa experienced strong, heat inducing tides, this finding led to the tantalizing suggestion that a water ocean might be present below the moon's surface. The data were of insufficient resolution to allow much more than theoretical speculation, and the Galileo observations were awaited with eagerness.

The Galileo images did not disappoint. in a June 1996 image, strong evidence appeared for surface cracking into ice floes, reinforcing a Voyager interpretation. Then the close Europa flybys found the first direct evidence of cryo-volcanism on a Jovian moon. These were followed quickly by apparently clear evidence of what appear to be icebergs now apparently frozen into place, but which appear to have been floating on some substrate that is difficult to conceive of as anything but liquid. But while increasingly compelling, there was as yet no unequivocal determination of the existence of a global ocean on Europa.

About the time of these discoveries, the Jet Propulsion Laboratory began advanced studies of a mission called the Europa Orbiter which would determine if an ocean is present and the thickness of the overlaying ice layer. If a thin ice layer could be confirmed, future spacecraft could be designed to penetrate the ice and look beneath it's surface. Data from Galileo and IUE indicate that materials other than ice, including sulphur, are present on the surface of Europa. Over time, these materials could conceivably be charmed into the water/ice below. It is this material (probably including organics), the presence of water, and the tidally-driven internal heat source which intrigue scientists who speculate on the possibility of life in the oceans of Europa.

The current design for the Europa Orbiter (see Figure 2) would take about three to four years to reach the Jovian system and an additional one and a half years to reach orbit around Europa. The mission consists of one month in orbit around the moon taking data and relaying the data back to Earth. The mission duration is driven primarily by the intense total ionizing dose radiation levels present in the Jovian system. Even with the short l ifet ime, the mission is scientifically engaging and rich and would lay the groundwork for future missions to Europa and other Jovian moons such as 10.

For the Europa mission, the X2000 First Delivery avionics bus will be interfaced with a 650 kg wet mass dual mode bipropellant propulsion module. This will provide for attitude control, Trajectory Correction Maneuvers (l'CM's), Jupiter Orbit Insertion (JOI), and Europa Orbit Insertion. The propulsion module is also designed to structurally support an experimental microspacecraft probe which would separate from the flight system, deorbit, and land on the surface of Europa to conduct surface science.
One proposed Europa science suite features a radar sounder to remotely determine the depth of the surface icc and determine if a liquid water ocean exists beneath it. Visible and thermal imaging is also included to map the surface and

determine composition and structure. Accurate tracking of the spacecraft orbit, in conjunction with a laser altimeter, will be used to determine the tidal flexing of Europa and provide key information on the internal structure and nature of possible subsurface oceans.

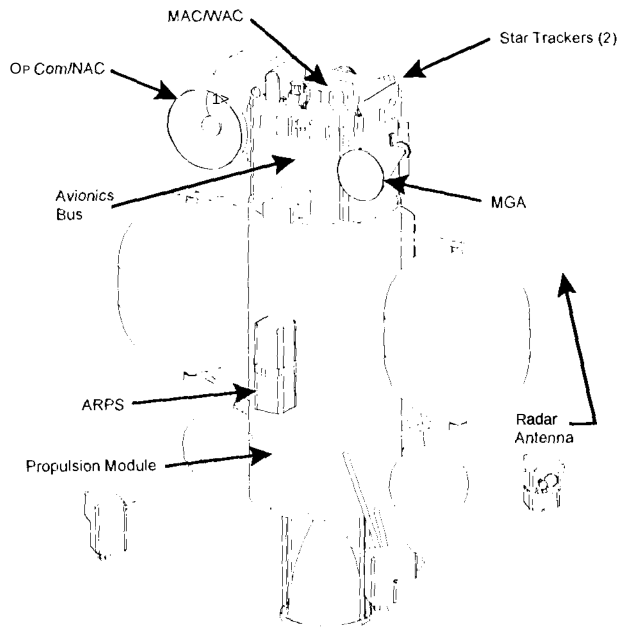

Figure 2: **Europa** Orbiter Spacecraft

Because spacecraft lifetime in orbit at Europa is severely constrained by the radiation environment (2 Mrad/month), a high data rate downlink is needed to return all of the surface imaging mapping data desired within the expected lifetime of the mission. For this reason, optical communication is baselined and included in the X2000 First Delivery bus. Ibis is expected to provide 100 kb/s compared with about 10 kb/s that could be obtained with a Ka-band fixed antenna that could fit within the launch vehicle payload fairing.

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Pluto is the only planet in our Solar System which has not been explored by a spacecraft. Pluto and it's large moon Charon form a binary system which has an orbit varying dramatically in distance from the Sun. Currently, Pluto's orbit is within the orbit of Neptune, but 124 years hence, it will reach an aphelion of 49 AU. This variation in orbital distance causes Pluto's atmosphere to sublimate (or condense) as the distance alternately decreases and increases from the Sun.

Even with the long flight times of nine to ten years, the Pluto/Kuiper Express mission is designed to reach Pluto/Charon while there is still a sensible atmosphere. [nobody knows when, or even if the atmosphere will "collapse"--it may just fade away. I'here arc many conflicting opinions all based on the same very limited data]. Characterization of the Pluto/Charon system will help answer questions about this unusual binary system and will contribute to our understanding of the formation of our Solar System.

After a fast reconnaissance flyby of the binary system, the trajectory will be altered to fly by a member of a group of objects referred to as the Kuiper Disk objects. Kuiper Objects, predicted in the late 40's by Edgeworth and Kuipcr* were only discovered in the early 1990's yet now there are several dozen of these objects catalogued. These small objects form a disk around our Solar System and arc believed to remnants of the formation of the Solar System and the primary source of short period comets. By studying at least one of these objects, scientists hope to learn more about the possible origin of the volatiles which form the Earth's atmosphere and oceans.

"I'he extreme distance from the Sun, long lifetime and fast flyby speed make this a very challenging engineering mission as well as an exciting science mission. The Pluto/Kuiper Express spacecraft is depicted in Figure 3.

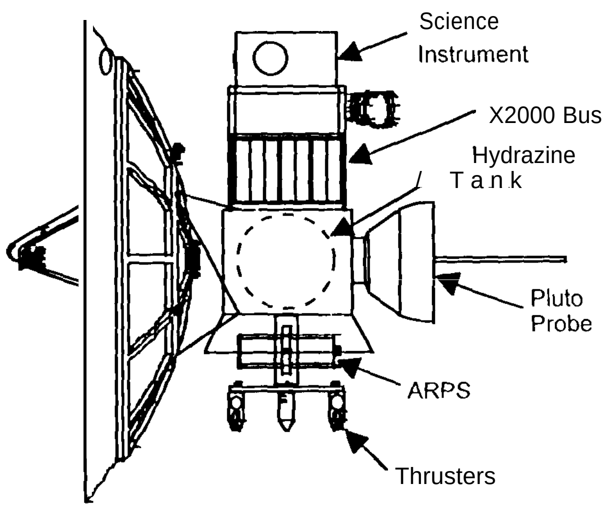

Figure 3: **Pluto/Kuiper** Express Spacecraft

For Pluto/Kuiper Express, the X2000 First Delivery bus will be mated with a 20 kg wet mass hydrazine monopropellant propulsion module. Ibis will provide for attitude control, TCM's, a probe deflection maneuver at Pluto, and retargeting to Kuiper disk objects. The propulsion module is also designed to structurally support an experimental microspacecraft probe which would be separated from the main spacecraft and targeted to conduct atmospheric science. A proposal is under study to include an inflatable ballute/air bag that might enable the probe to decelerate and survive hard landing in order to conduct some sLn'face science.

An X-band uplink sufficient to perform radio science of Pluto's tenuous atmosphere is desired for the encounter. In addition to the RF link, optical communication is under study for the Pluto mission, since it is an option on the X2000 First Delivery bus. About 2 Gb of data is expected to obtained during the few hours of the Pluto primary encounter. This will be stored onboard for transmission back to Earth during the weeks following encounter.

Deep Space 4

The New Millennium Deep Space 4 mission is a challenging journey to rendezvous with Comet Tempel 1, land on its surface, recover a sample, and possibly return it to the Earth. As shown in Figure 4, the flight system uses a Solar Electric J'repulsion (SEP) module to provide the 10.S km/sec delta V required to perform the mission. The SEP module is "dumb", and requires commanding from the attached Lander module to operate for most of its modes.

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Figure 4: 1) S-4 **Spacecraft**

The Lander module contains most of the flight system avionics, plus comet surface science, anchoring, and sample acquisit ion equipment in a separate module on the Lander. After arrival at the comet, the flight system will go into orbit around the nucleus, and the Lander wi II separate from the SEP module, set down on the surface, anchor itself, and conduct a series of science experiments, including the acquisition of a some samples. During surface operations, the orbiting SEP module is in a passive spin stabilized mode, with its High Gain Antenna (HGA) pointed at the Earth, so it can serve as a radio relay for the Lander.

At the completion of surface science, the Lander will jettison its anchoring module, leave the comet surface, and rendezvous and dock with the spinning SEP module. The samples will be transferred to an Earth return entry capsule. Then the entire flight system, under control of the attached Lander module, will revert to full attitude stabilization, power up the ion thrusters, and return to Earth. Just before arrival, the flight system will put the Earth entry capsule into the correct corridor, and then jettison the capsule for recovery on Earth.

Because of severe mass limitations, the Lander must be highly optimized, both structurally and functionally. For these reasons the X2000 First Delivery bus cannot be used "as is", but many components from it can be utilized in the custom designed multifunctional bus for DS-4. A pared down single string version of the X2000 microelectronics will be used, along with the Advanced Stellar Compass (ASC), Inertial Measurement Unit (IMU), and their ground support equipment. Many software elements from the First Delivery bus will also be utilized.

Mars '03 Orbiter

The Mars '03 orbiter is currently planned to be a simple bare bones communications relay for the ambitious landed science package in the Mars '03 mission. A pared-down single string version of the X2000 avionics may be used, along with the attitude sensors, in a low mass custom bus design. Extreme low mass is necessary to minimize the cost of the launch vehicle for the mission.

Mars Ascent Vehicle

The 2004 Mars Sample Return mission will be one of the most challenging interplanetary ventures of the early 21st century. Even more so than the '03 orbiter, extreme measures must to taken to minimize mass to perform the mission with a launch vehicle small enough to fit within the cost cap. The Ascent Vehicle is the most mass critical, since all of the propellant required to boost it back into Mars orbit must first be soft landed cm the Martian surface. A pared down single string version of the X2000 avionics may be used, along with the attitude sensors, in a low mass custom bus design.

Solar Probe

Solar Probe is an exploratory mission to our star, which gives us life and whose effects on the earth and solar system are profound. We are only beginning to undertsand the relationship between the sun, its atmosphere (the corona), and the solar effects on the earth. The recent observatory missions (YOHKOH and SOHO) have given us new data to answer old questions and create new questions that can only be answered by the Solar Probe. The mission is designed to take scientific instruments into the solar atmosphere to within 3 solar radii (2. 1 Gm) of the Sun's atmosphere where they wi II make measurements to determine what causes the heating of coronal particles (to well over a million degrees), as well as what are the sources and acceleration mechanisms in the solar winds. The low altitude passes of the Solar Probe spacecraft over the polar regions will allow imaging that has here-to-fore been impossible and at perspectives that will never be attained from near Earth observatories.

This close approach to the Sun requires that several technical challenges be undertaken. Materials in the exposed portions of the spacecraft must survive the extreme temperatures during the encounter with the Sun. An integral heat shield and high-gain antenna design has been developed to shield the spacecraft from the extreme heating while providing high-rate real-time communication with the Earth during the critical close encounter period (see Figure 5). This innovative concept is accomplished through the unique trajectory and a new application of high temperature materials technologies. The trajectory uses a Jupiter gravity assist maneuver to provide the unique quadrature geometry at perihelion which enables the shield/antenna combination.

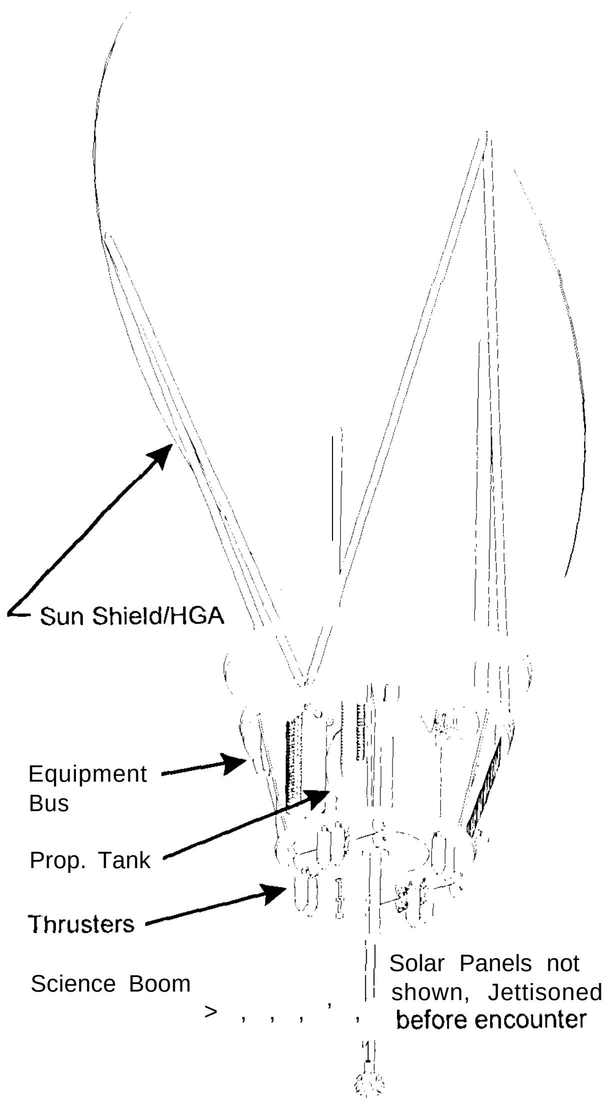

Figure 5: Solar Probe Encounter Configuration

A diverse set of power sources, including solar arrays and batteries, are required to survive the extremes in solar radiance between the dim cold of a Jupiter gravity assist flyby and the extreme heat of a close encounter of the sun.

Because of the unique shield geometry and thermal requirements of the mission, the X2000 First Delivery bus cannot be used "as is", but many components from it can be utilized in the custom designed bus for Solar Probe. A customized version of the X2000 microelectronics will be used, along with the Advanced Stellar Compass (ASC) and their ground support equipment. Many software elements from the First Delivery bus will also be utilized.

The propulsion requirements for Solar Probe are very similar to Pluto Express, therefore Solar Probe can use the same tankage and components at a recurring cost. The Propulsion Module integration structure for Solar Probe will be different from Pluto Express, however, due to the unique shield geometry and thermal constraints.

Integrated Requirements

Specific performance requirements for the flight missions are presented in Table 1, along with the X2000 First Delivery expected capabilities. The shaded rows indicate items that are not included within the scope of the First Delivery system, but the architecture and interfaces are designed to enable those characteristics in the flight mission systems.

3. X2000 FIRST DELIVERY BUS

The First Delivery spacecraft bus is shown in the exploded view, Figure 6. The shaded components are mission unique elements for the Europa Orbiter mission. Figure 7 indicates how different modules can be used as building blocks for an entire mission set based on the X2000 First Delivery components plus mission unique propulsion modules, science, and other specialized equipment.

Microelectronics

In order to accommodate the diverse requirements of the multiple missions identified above, the architecture of the X2000 First Delivery microelectronics must be scaleable. This has a number of implications, one of which is the need for standard interfaces. This will allow modules to be added or removed from the system to meet the requirements (performance, mass, power, volume) of a specific mission.

The microelectronics are a highly integrated stack of standard sized (10 cm x 10 cm) Multi-Chip Modules (MCM's) and Chip-On-Board (COB) subassemblies. Both of these technologies utilize unpackaged bare microchip die directly bonded onto a standard sized substrate. The substrate contains all of the printed circuit traces required for electrically connecting the die together. At the periphery

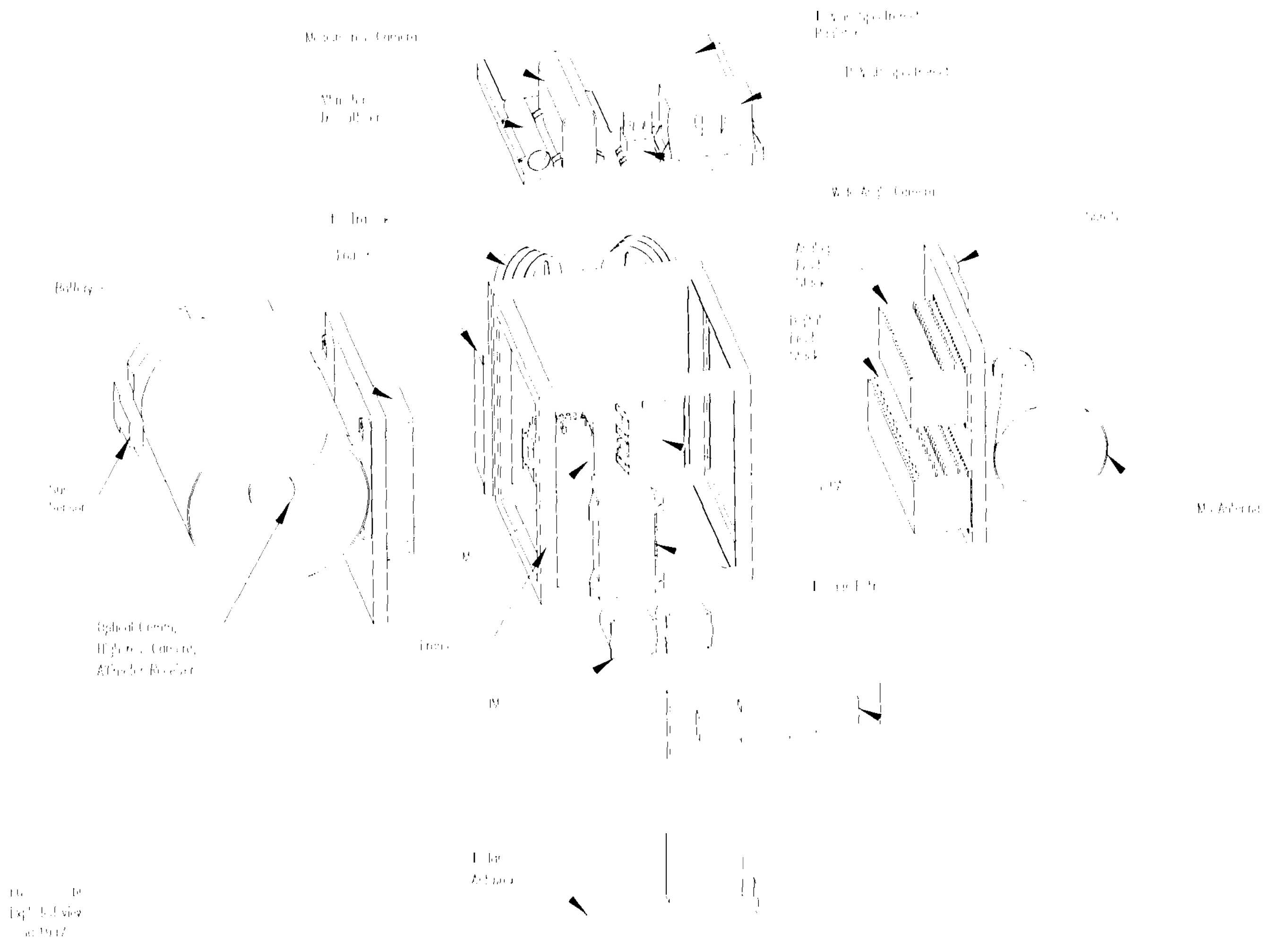

Figure 6: X2000 First Delivery Bus, Exploded View

of each of these subassemblies are all of the electrical terminals required to interface the subassembly with other elements of the spacecraft. These subassemblies are often referred teas “boards”o r”slices”.

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Figure 7: X2000 **Based** Modular Building **Blocks**

The sl ices are stacked on top of one another using a new packaging technology which-allows different combinations of MCM's and COB's, or even conventional PC boards, to be assembled together in any order with the electrical terminals on the periphery in contact with those of the adjacent slices (Figure 8).

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Figure 8: X2000 Micro-Electronics Packaging

‘1’here are standard terminal locations for data bosses, power busses, and other signals, so that these can be reconfigured in a plug and play fashion. To change between single string and dual string configurations requires only the removal or addition of slices. In the same manner, more memory or processors can be added, or individual slices can be upgraded to the next generation, simply by replacing those slices with the new ones, leaving the remainder of the slices in the stack unchanged.

The performance of the system must not be affected by the addition or removal of modules. As the number of modules increase, the system should not degrade. This is achieved with a multi-master bus, avoiding the performance bottleneck that might occur with a dedicated master. Each module in this architecture is individually coupled to the bus and has its own resources.

In the X2000 architecture, the role of the flight computers is flexible. This allows for scalability, allowing the number of processors to be increased or decreased depending on mission requirements. It also allows the system to be very fault tolerant, so that if one computer fails, another can take over its tasks. And, finally, it allows the system to conserve on power. By sharing the load, each processor can run at a lower speed and save power.

Figures 9 and 10 demonstrate the variety of uses that can be realized with the X2000 architecture. Figure 9 shows the full, dual string stacks to be utilized for the Europa and

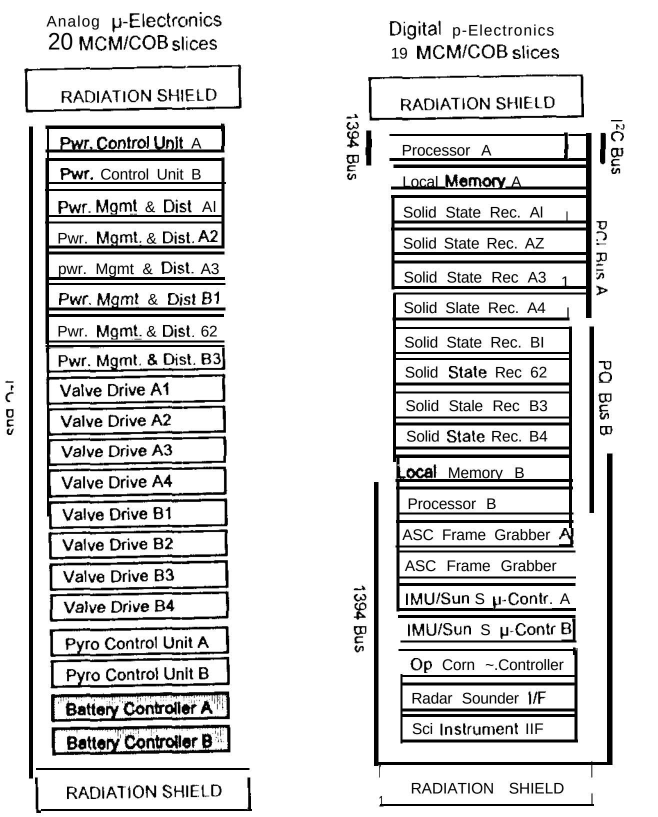

Figure 9: **Dual-String Micro-Electronics** Stacks

Pluto missions. Although there are 39 slices in the two stacks, there are only 8 different types of slices that must be designed and qualified, Figure 10 shows the single string, more modest capability, "short stack" that can be used on missions like Mars Sample Return or DS-4 which are highly mass constrained and don't require the same level of performance and redundancy as the Europa and Pluto configurations. The radiation shielding is also modular and tailored to the requirements of each mission.

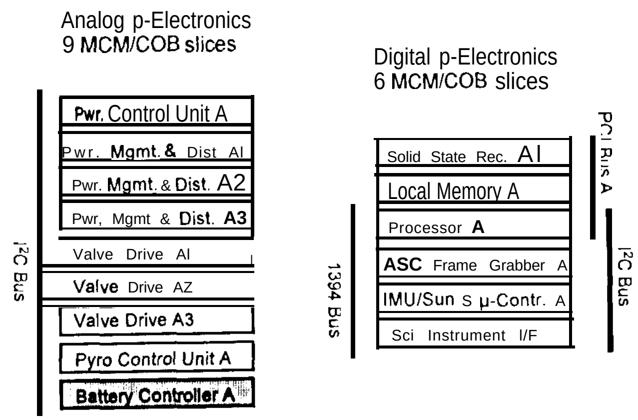

Figure 10: **Single-String** "Short Stack"

Software and Autonomy

From the software's point of view, the flight micro-electronics stack resembles a local area network in a laboratory, multiple powerful processors running standard open operating systems and languages which communicate over high bandwidth interconnections. Each processor (flight computers and microcontrollers) will run a commercial real-time network-aware operating system. The X2000 software will be distributed, multi-threaded, and object-oriented. The primary implementation language will be Java. Thus, the on-board software system will look more like a sophisticated lab system than a classical flight system.

Using an inherently soft real-time architecture for an inherently hard real-time system may at first seem risky. However, the Mars Pathfinder project demonstrated hardware-software interface design principle which enables such an approach: Many of the software-to-hardware protocols on Pathfinder were "fire at time" or "fire at time with duration." This style of protocol was applied to thrusters, pyro devices, and certain other relays. Many hardware-to-software protocols provided timestamps for events or data. By implementing these protocols, the software real-time response requirements were slackened from being that of the event durations to that of the event period, which often differed by several orders of magnitude. Note that on a system which must be resilient to failures, a real-time response requirement generally must include fault responses as well as nominal responses. Hence, this easing of deadlines bad a dramatic effect on the entire software system.

On the X2000 system, we are going yet further with this design principle: all devices will be so controlled, and all data will be timestamped. The Internet standard network time protocol (NTP) [1] enables this approach while still using asynchronous multi-master networks to link computing nodes with low quality clocks (the spacecraft will have an ultra-stable clock for communication and navigation purposes which will serve as the NTP master clock).

Most of the code will be implemented in Java. The small amount of code which requires data to be specifically located in memory will be implemented in C; e.g., part of the device drivers. The even smaller amount of code which deals with specific instructions will be implemented in assembler; e.g., the bootstrap and certain low level kernel support routines. Finally, those behaviors which require very fast response will be implemented by hardware. A significant and ongoing proof of concept effort in JPL's Flight System Testbed has proven the veracity of this approach.

Mars Pathfinder was aggressive on several software technology fronts, and very successful by any metric. Since no technique was tried pervasively, the full lifecycle effects of the various techniques could be easily compared. The techniques which proved highly effective were: object-orientation, message passing, asynchrony, responsible objects [2], goal oriented commands, and the Law of Demeter [3, 4].

Object-orientation, message passing, and asynchrony are widely understood today, but the other concepts are still new to many. "Responsible" when applied to objects is not jargon: it is the common usage of the adjective. A responsible object performs both nominal and foreseeable off-nominal behaviors. A responsible object only reports an error when things have gone very wrong, and a fault condition needs to be triggered.

"Goal oriented commands" are a slight change in attitude: instead of telling an object what to do, one tells an object what to achieve. In many cases with low level objects, the difference is nearly non-existent: instead of turning a device on, the goal would be "be on." The effect is that the object performs some closed loop control, rather than an open loop response: in this example, the object would only throw its power relay if it was not already on, and in many cases would strive to keep itself on. Goal oriented commanding implies that behaviors are closed loop.

The "Law of Demeter" (LoD) is simply stated "an object acts only on its state, an event, and the data provided with the incoming event." It turns out that LoD implies responsibility, asynchrony, publish, and subscribe messages [5, 6]. Post analysis of Pathfinder has shown that the LoD leads to remarkably little inter-object communication [7].

Like most software systems, legacy software will be incorporated in order to achieve the cost and schedule advantages of software re-use. For the X2000 first delivery, the attitude control system (ACS) will initially be taken from the New Millennium Deep Space One (DS-1) spacecraft. This object-oriented ACS subsystem is now third generation. Its basic object architecture was initially defined for Cassini, refined for Mars Pathfinder, and refined again for DS-1. The Cassini implementation is in Ada, while the Pathfinder and DS-1 implementations are in C. Incorporating this ACS software is straightforward, as its inter-process communication model is message based, and adheres to the Law of Demeter.

The autonomy mechanisms of the X2000 system will be based on the current state-of-the-art in AI technology, some of which were implemented on the Mars Pathfinder Sagan Memorial Station. Rather than being based on large, generalized architecture infrastructures implemented in LISP and using symbolic reasoning and extensive modelling, Pathfinder instead based its autonomy on the new wave of AI which began in 1985 with the work of Rodney Brooks and his robotic insects. This new wave of AI was originally called the Subsumption Architecture but has been more recently referred to as Emergent Behavior.

Emergent Behavior is a scaleable technology, in that the amount of autonomy exhibited by the system increases with time and bLld.get. It allows a bottom-up software construction process, which allows the software to remain off the critical path (ahead of the hardware). LISP is no longer a requirement, or even necessarily a desirement, of such systems. Emergent behavior, like responsible objects, meshes perfectly with the Law of Demeter, and hence can be applied easily to distributed systems by developers who don't consider themselves AI experts. On Mars Pathfinder, the fact that the software was being, implemented using state-of-the-art AI wasn't made clear to most of the developers until after the system was delivered.

Another technique from current AI research is resource contention resolution using reflexive behavior derived from experiments in biological systems. A result of these experimental efforts which appears directly applicable is the vestibule-ocular reflex (VOR), which allows eye pointing to be achieved with conflicting requirements (track target or focus on detail) and head movement which may be triggered by any other mechanism. The VOR control algorithm which has been derived via biological system identification turns out to be a very simple and conventional closed loop control algorithm.

In other cases, such as in prioritization, market based mechanisms (using both cost-of-service and need-for-service factors) appear very effective while still being reflexive and simple.

U'here arc, of course, certain activities on a spacecraft which cannot be handled by a purely reflexive, reactive system. In many cases, the goal based commanding encapsulates such proactive behaviors. For example, the Pathfinder command "Downlink_ Opportunity" will warm up (as needed) and configure (as needed) the communication hardware devices prior to the communications window.

In very rare situations, we expect that on-board planning will be required. The Achilles heel of planning systems is that they are highly non-linear. If the number of factors involved in planning remains low, and the number of activities planned remains low, then planners are tractable. By utilizing the other AI approaches mentioned above, it appears that only a handful of events will require planning per day even during intensive operations such as Europa orbiting. This will finally allow us to implement on-board planning on a deep space mission.

Telecommu nications

The First Delivery bus will have an Optical Communications (Op Com) Terminal as its primary means of uplink and downlink communications. This is a 30 cm aperture telescope with an Active Pixel Sensor (APS) as the receiver detector for the uplink laser signal from Earth. There is an onboard laser with a precision tracking and pointing mirror to provide the down] ink back to a 10 m aperture "photon bucket" receiving station on Earth. The spacecraft provides pointing with a 2 mR accuracy, and the internal tracking mirror uses the visible image of the Earth as a tracking reference to provide steered laser pointing with an accuracy of2 μR.

In addition to the Op Com Terminal, there is an Auxiliary Radio system that provides X-band upl ink and downlink capability with a Medium Gain Antenna (MGA). Some missions may also add omnidirectional Low Gain Antennas (LGA's). This enables communication under certain situations where the spacecraft cannot maintain 2 mR pointing of the Op Com terminal to Earth. This also covers periods of time when an Op Corn ground station may not be available.

The Op Com terminal is being designed to also serve as a science instrument, providing high resolution imaging and serving a receiver for a separate laser altimetry instrument. Some missions may choose to go all-radio for their communication, and not carry the Op Com terminal. Ka-band is also an option for the X2000 bus by using a different Solid State Power Amplifier (SSPA).

Sensors and A ((if ude Co ntrol

The engineering sensors arc plugged into the spacecraft using a standard I^2C low-to-moderate data rate sensor bus. This includes pressure and temperature sensors, sun sensors, and the inertial Measurement Units (I MU's). The exception is the Advanced Stellar Compass (ASC) star tracker which plugs into the 1394 bus, provided for all of the high data rate spacecraft components.

The primary attitude reference for the flight system is the ASC, developed by the Technical University of Denmark, based on the design of the Oersted satellite's star tracker. It operates by acquiring star images with a small, wide field of view CCD camera head unit, equipped with a 19mm, f/0.7 lens. It is projected to weigh about 1.0 kg (including light baffle), use S W of power (with the frame grabber), and have an accuracy of approximately 25 μR absolute RMS. Two images per second will be taken, which in combination with the 5 mN thrusters, will give the X2000 bLrs a pointing knowledge of I mR and stability of 10 μR/sec.

The Attitude Control Subsystem (ACS) also has an IMU to provide a pointing reference during propulsion module burns. The Inertial Measurement Unit provides 3-axis rate information from a fiber optic gyro and 3-axis acceleration information from a miniature silicon accelerometer. The gyro bias stability is less than I deg/hour (1 sigma). The fiber optic gyros, silicon accelerometers and electronics are combined into one small package, weighing less than 1kg.

The Sun Sensors are used as emergency fault recovery attitude sensors, co-boresighted with the RF antenna, allowing communications with Earth by merely pointing the antenna to the Sun. The angle measurement of the SLrn Sensor will be approximately 30 degrees from the reference vector with a mini mom accuracy of 2 mrads for angles < .1 rad and **3°/0** thereafter. Sun presence detection is Lrp to 60 degrees from the reference vector.

Bus Structural and Thermal Design

The baseline bus design for the First Delivery is shown in Figure 6. Six rectangular composite honeycomb panels attach to a lightweight titanium frame to form a stiff cubical structure to which components arc mounted, both internal ly and externally. The panels are modular and can be independently removed for access and service.

Components are laid out so that functional subsystems are on their own panels, to faci t itate cleaner interfaces and assembly. For example, Telecom components are all on one panel, except for the MGA. Science instruments are on another panel. Attitude sensors are on one panel, except for the small sun sensors. And the digital and analog microelectronics stacks are integrated together on one panel.

The inside of the bus is maintained at a temperature range of -30" C to -10° C. Heat is obtained both from the operating electron its, and from thermal communicant ion with the attached propulsion module, which in the case of Pluto Express and Europa Orbiter is warmed with waste heat from an attached Radioisotope Power Source (RPS). Radiative heat loss from the bus is controlled by thermal blankets, and thermostatically controlled louvers arc on onc of the bus panels to correct for variations in the heat loads inside the bus.

Propulsion Modules

The X2000 First Delivery bus is designed to interface with a variety of mission specific propulsion modules, covering the range of cold gas, hydrazine monopropellant, bipropellant systems, solid rocket motors, and SEP. The avionics and software arc designed to provide standard data bus and power bus interfaces, and software wi II be in place to enable the control of these modules by the bus.

Power Sources

The Pluto and Europa missions are being designed to be powered by RPS, but the X2000 bus is also capable of being powered by solar arrays. The First Delivery bus is designed to include a battery and charge control electronics. For Pluto and Europa, the battery is used for brief periods where power consumption must exceed the output of the RPS, mainly during propulsion module burns. For solar powered missions, the battery will be charged by the arrays.

Science Payload Accommodation

Science payloads are accommodated by using standard data bus and power bus interfaces. Regulated power is provided at the voltages described in Table 1. If elements of the instrument must operate at other voltages, then the instrument must provide its own conversion for those items internally. The 1394 bus can handle science instrument data rates of up to 75 Mb/see, depending on what other traffic is on the bus at that time.

Mechanical and thermal interfaces will most likely be custom to each mission, but the intention is to integrate science onto the top bus panel shown in Figure 8. In this manner, al l of the mechanical interface customization is limited to that one modular panel, leaving the rest of the standard bus unchanged.

Probe Support Subsystems

A number of missions utilizing the X2000 bus (or components) have attached probes for which a relay link must be provided. These would be mission specific items that would attach to either the propulsion module or the bus. There is a potential for commonality between some of the missions in the radio link hardware and software. There might also be potential for commonality in the probe attachment and release interface, hardware, and support equipment.

4. MISSION DATA SYSTEM

in al l past and present J} 'l, deep space missions, there arc four distinct data systems: the testbed system, the flight software on-board the spacecraft, the upl ink system, and the telemetry and archiving system (the latter two often called the Ground Data System, but they are in fact two distinct streams of subsystems which cannot communicate electronically). The X2000 software system instead embodies a new concept of a single Mission Data System (MDS) which is a collection of end-to-end services, and is used throughout the life cycle of the mission, through design, development, integration and test, operations, and archiving.

End-to-end services means that a subsystem (e.g., a spacecraft battery) provides device driver flight software, tactical goal oriented flight software (charge battery), strategic goal oriented flight software (achieve and maintain maximum charge prior to orbit insertion), planning models for the planner (same planner on-board as on-ground as for system engineering scenarios), performance analysis based on telemetry, and commanding. This is in fact no increase in scope for the project: since all tasks already need to be done for each subsystem. The difference is that now a subsystem is responsible, and empowered, to provide a complete pllrg-arid-p!ay package.

The technologies which enable this new MDS concept arc all derived from the Internet and the World Wide Web (WWW). The new Deep Space Terminal (1)S-1), a new fully automated communication service of the Deep Space Network (DSN) which has been demonstrated on Earth orbiting spacecraft, is the cornerstone. The DS-T will appear as a server on a world-wide NASA intranet which, other than its limited access, is identical to the Internet. Objects, files, and packets will bc stored on the DS-T to bc forwarded to the spacecraft whenever connection is established, with a dynamic but controllable prioritization mechanism. The same DS-T software will run on the spacecraft to handle the other end of the link. The DS-T will provide a packet database on both ends of the link, distributed across all the DSN sites on Earth, and possibly distributed across processors on-board.

The DS-T is scheduled to bc deployed well before the first spacecraft using X2000 MDS will be launched. However, until the DS-T is fully deployed, a simple gateway will encapsulate the existing JPL multi-mission ground data system and masquerade as a DS-T. This gateway wil l allow the existing JPL expertise to evolve the essential and extensive capabilit ics required to fully transit ion from the existing infrastructure to the new system.

Ground components of the end-to-end services will each provide a subsystem web server. This web server will connect with the DS-T using standard web protocols, and take advantage of push technology to obtain new telemetry from the spacecraft. The subsystem web servers can easily utilize legacy software via CGI (common gateway interface) to limit new development to new capabilities.

As with Mars Pathfinder, the end-to-end system used for development is the same as used for flight, and is available for developers from the time the project actually begins. 'l'his, combined with the bottom-up software approach, allows the software to stay off the critical path, to stay ahead of the hardware.

X2000 is taking the complete Mars Pathfinder MDS as a starting point. This system is an integration of the four classic distinct JPL data systems, and already has some mechanisms implemented using World Wide Web (WWW) technologies.

Ncw end-to-end services are already under development. For example, highly automated Navigation and Communication subsystems have been under development for two years. These will probably be the first two subsystems incorporated in the X2000 MDS.

A key goal of the new M DS is to allow subsystems to easily share information and code. Again, Web technologies enable this. CGI and Java Beans will be used to allow subsystems to export their data, algorithms, and objects in a standard way. Java Beans can be assembled using Drag'n'Drop tools to glue together applications from parts provided by various groups.

Planning is a part of all spacecraft missions. On Mars Pathfinder, we advanced the planning task to support system engineering as well as operations. This early use of planning allowed many scenarios to be rLrn early on, which uncovered several operability problems before designs were finalized. The result was a very easy to operate spacecraft that required almost no planning during operations.

The X2000 MDS will likewise incorporate a planner, but this planner will be web-aware. Rather than re-implementing models in the planner, models can be exported by the subsystems as CGI or Java Beans. Also, the actual testbed (which is also on the Web) can be used instead of models. The same planning engine wilt be flown, which will allow planning models to be well understood during development, integration and test, before ever being flown.

A final key capability of the X2000 MDS is the support of automated testing. An extensive body ofrescarch and development is backing this capability. Certain automated testing tools arc already on-line, and new tools arc being developed based on machine learning and genetic algorithms (which search the test space in a parallel fashion, finding local disturbances).

5, COST BENEFITS AND PERFORMANCE PENALTIES

The x2000 First Delivery is planned as a multimission bus for the Europa and Pluto missions, and the recurring cost for a flight qualified bus is expected to be very low. The propulsion modules and science packages are unique; however, and they will bc more of a factor in the total cost of those missions. These mission unique costs are borne by each individual mission, bLrt by using a common bus, support equipment, test equipment, and common ground and flight software modules, each mission can reduce its integration and test costs.

The modular architecture of the X2000 First Delivery system allows for customization of the electronics for each individual mission. Each mission can chose the "slices" which are appropriate for it's own needs. Performance penalties arc minimal across the diverse set of missions by allowing each customer to pick and choose components from the suite of options. Redundancy and capability can be selectively modified within subsystems as well as across the system.

For Europa and Pluto, there are mass penalties with using a common modular bus structure capable of supporting either of the two science packages. Optimization which would normally be used to tailor a system for a given mission cannot be done across several users. For example, were a mission specific bus structure to be developed for the Europa mission, there could possibly be a few kilograms of mass savings, bLrt then it would not be usable for the Pluto mission with its science package.

The common bus design also reduces the thermal control cost for the second mission. Even though the science instrument thermal interface is unique, most of the rest of bus is identical, enabling reuse of most of the models and analysis. The commonality will also allow for reduced thermal testing.

Due to extreme mission unique constraints, the Mars, DS-4, and Solar Probe Missions will not be able to use the entire build-to-print spacecraft bus, but will usc many of the subsystems and components at a recurring cost. Because Of this customization, the cost savings, although substantial, will not be as great as for Pluto and Europa. But there will also be little in the way of performance penalties.

6. CONCLUSIONS

The X2000 First Delivery bLrs is pushing the state of the art in achieving a highly integrated, yet modular and scaleable, spacecraft architecture that will have high performance capabilities, yet very low mass. It is being designed to meet the composite requirements of a very challenging set of interplanetary missions to be performed in the first few years of the 21st century. The combination of these capabilities with a very low recurring cost for the system will enable the mission set to be performed within the highly constrained funding limits for these programs.

The X2000 Mission Data System presents daunting challenges in management and in technical execution, requiring considerable sophistication. It is probably not cost effective to replace all of the legacy systems which have evolved over decades. It is also not reasonable to expect that the technology developed for the X2000 First Delivery will not become obsolete with time. Therefore, the eventual Mission Data System will include legacy code whose implementation may be obsolete but whose function is still vital, new code which is state-of-the-art, and code which is yet to be imagined that will be implemented with whatever comes after.

Fortunately, the World Wide Web enables legacy systems to be easily incorporated, subsystems to easily communicate and collaborate, and new technologies to be adopted when and where needed The X2000 MDS will stretch the World Wide Web across the Solar System.

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Table 1: Flight Mission Requirements vs. X2000 Capabilities

Components and Performance Parameters	)00 Baseline Capability elv Oct '00	Flt Miss Rqmts a Orbiter Oct '00	P uto Express Need Ott '00	Champollion Need Ott '00	Mars '04 .scent Avionics	Comments
Avionics Bus (system)			100 kg			High perf system w/3 computers no Sci Prop or rad shielding
Dual Strong Mass (unshielded)	92 kg					
Dual String Mass (shielded)	120 kg	)0 kg				
Single String Mass (all RF)	43 kg				30 kg	Minimal system w/1 computer, solar array instead of ARPS
Power	100W			15 W		Does not include Propulsion or Science
Volume						
Radiation	)0 Krad	00 Krad	200 Krad	) Krad		Combination rad hard pads and shielding
Maximum Operating Temp				30° C		Europa and Pluto want thermal qual'ed system
Minimum Operating Temp				45 c		
Electronics Packaging	) Stack	) Stack	3D Stack	F unc Str	3D stack	Pkg design sppts both Stack and MFM implmtn
SIC Pointing Accuracy	2 mR	2 mR	2 mR		17 mR	3 σ
sic Pointing Know'edge	1 mR	1 mR	1 mR		2 mR	
S/C Stability	0 μR/s	0 μR/s	10 μR/s			
Spacecraft Data Subsystem					.20 MIPS	Speed shown is for 1 processor only
Processor Speed	1 MIPS	o MIPS	50 MIPS	2 MIPS	want w/CPU	Per each of 3 CPU MCM's
Local Memory	20 Mb			16 Mb		Includes redundant memory
Mass Memory	000 Mb	000 Mb	4 000 Mb	340 Mb	need this	Baseline is I²C
Low rate sensor data bus	o kb/s				need this	RS465 serial I/F with 1553 data protocol
Med rate engineeing bus	)el eked				don't need	1394 bus
High rate science bus	)0 Mb/s	50 Mb/s	0 Mb/s			S/S mass, dual strg but w/3 CPU & 3 mem MCM's
Mass	3?kg			3 5 W		
Power at 275 MIPS				4 7 W		
POWerat55 MIPS				1 1 9 W		
Power at 22 MIPS						ludes battery management capability
Power and Pym Electronics				, 12, 28 V	*5 ±12, 28 V	t incl RPS shunt radiator, battery or shielding
Voltages	±5,±12,+				20 kg total	
Mass (single string)	2 7				)% Average	V needs peak 90%
Pwr conversion efficiency						V needs star camera and framegrabber I/F
Star Tracker				38 μR	291 μR	
Accuracy, Pitch 8 Yaw	45 μR			216 μR	291 μR	
Accuracy, Roll	270 μR				io IIF MCM	ass includes interface MCM at 4 kg
Mass	.8 kg					
Power	4 W					
Gyro				1 0 /hr	0 6°/hr	
Bias instability	1 0°/hr				0 7 kg	
Mass					1 2 8 W	
Power	1 2 0 W					
Radiation tolerance						
Accelerometer				2 0 μg		
bias	1.5 μg				don't need	
Sun Sensor				9 mR	don't need	or angles .100 mR
Accuracy	2 mR				don't need	lass includes interface MCM at 4 kg
Mass	9 kg				don't need	
Power	1W					
Optical Com Package						Values are for Europa
Data Rate	100 kb/	130 kb/s				
Rqd S/C Pointing	2 mR	2 mR				or Europa 2 kg shielding must be added
Mass	11.0 kg					
Input Power	36 0 W	3 2 0 W				
Radiator f 0 v						X2000 is only supplying intefaces
RF Transponder		X-Bane!	X-Band	X-Band	X-Band	
Uplink Frequency	X-Band	yes	yes	yes		
Beacon Mode	yes			3 4 kg		
Mass	05kg					
Power	12W					X2000 is only supplying intefaces
RF SSPA		X-Band	X.Band	X-Band		
Frequency	X-Band	5 W	5 W	20 w		
Output Power	5W			80 w		
Input Power	1 7 W			1.8 kg		X2000 is not supplying this
Mass	0 2 kg					
RF Antenna						
Size and configuration	.2 m MGA	2 m M G		3 5 4 d		
Gain	200 dB	200 dB				
Mass	1 0 k g	1 0 k g		3 5 kg		